Peter Detzner, Jana Gödeke, **Lars Tönning**, Patrick Laskowski, Maximilian Hörstrup, Oliver Stolz, Marius Brehler, Sören Kerner

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Fraunhofer-Institut für Materialfluss und Logistik IML

SOLA: A Decentralized Communication Middleware Developed with ns-3

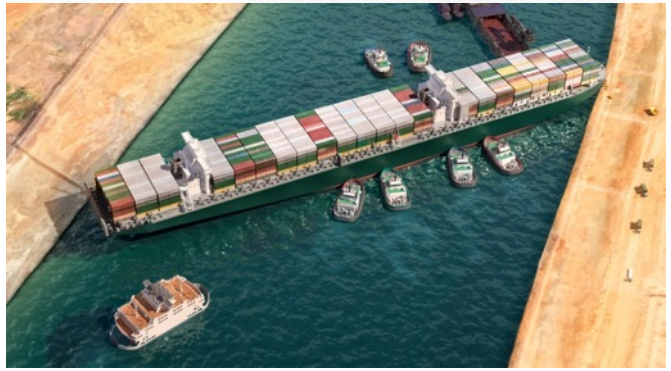
WNS3 2023, June 28–29, 2023, Arlington, VA, USA

Motivation

The world is changing…

Pandemic

Supply Bottlenecks



Flexibility **Transparency** **(Re-)Configuration**

Robustness **…**

Functionality **Scalability**

Customized Products

Mass Production

[BtV14], [LDE22], [Sta20]

Images: Adobe Stock

[BtV14] Bauernhansl, Thomas; ten Hompel, Michael; Vogel-Heuser, Birgit: Industrie 4.0 in Produktion, Automatisierung Und Logistik: Anwendung, Technologien, Migration. Wiesbaden: Springer Vieweg, 2014

[LDE+22] Lünsch, Dennis; Detzner, Peter; Ebner, Andreas; Kerner, Soren: SWAP-IT: A Scalable and Lightweight Industry 4.0 Architecture for Cyber-Physical Production Systems. In: 2022 IEEE 18th CASE, Mexico City, 2022

[Sta20] Statistisches Bundesamt: IoT Connected Devices Worldwide 2019-2030. https: //www.statista.com/statistics/1183457/iot-connected-devices-worldwide/, December 2020.

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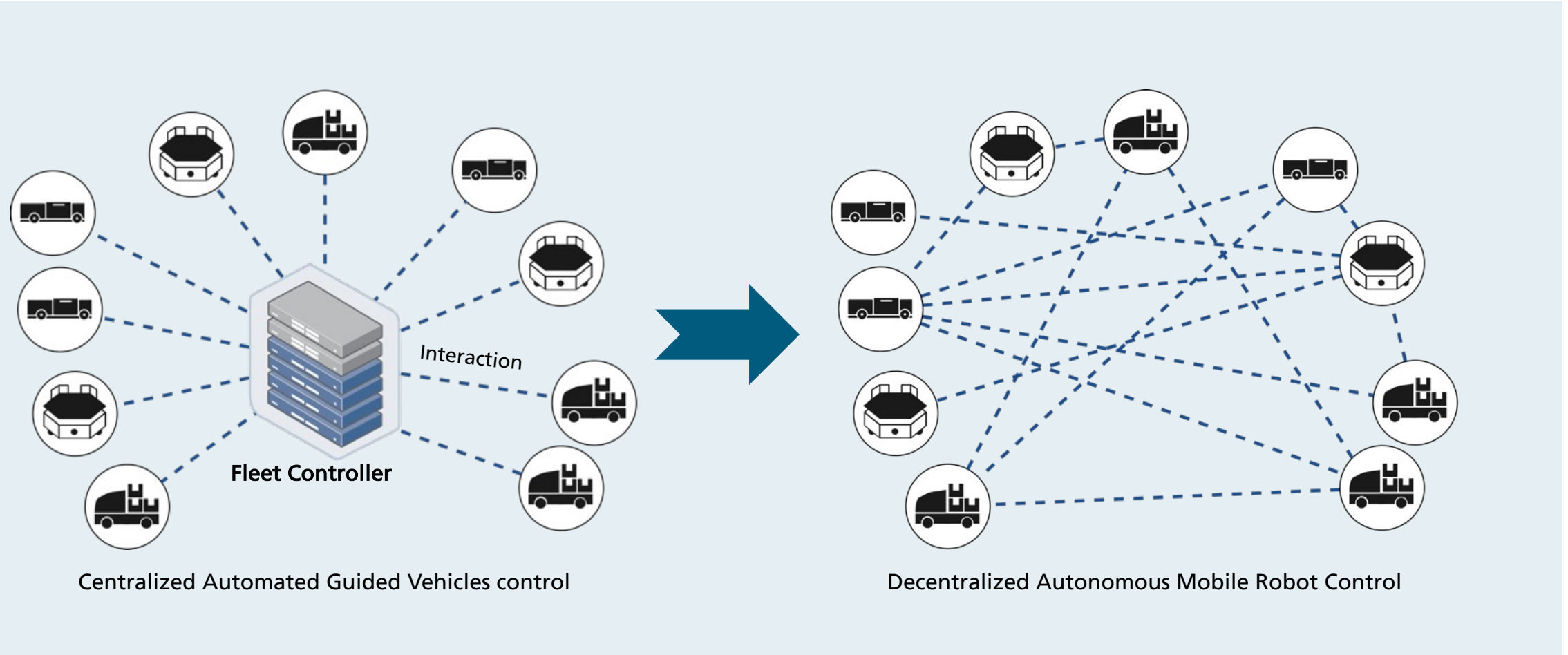
Paradigm Shift

From centralized towards decentralized control



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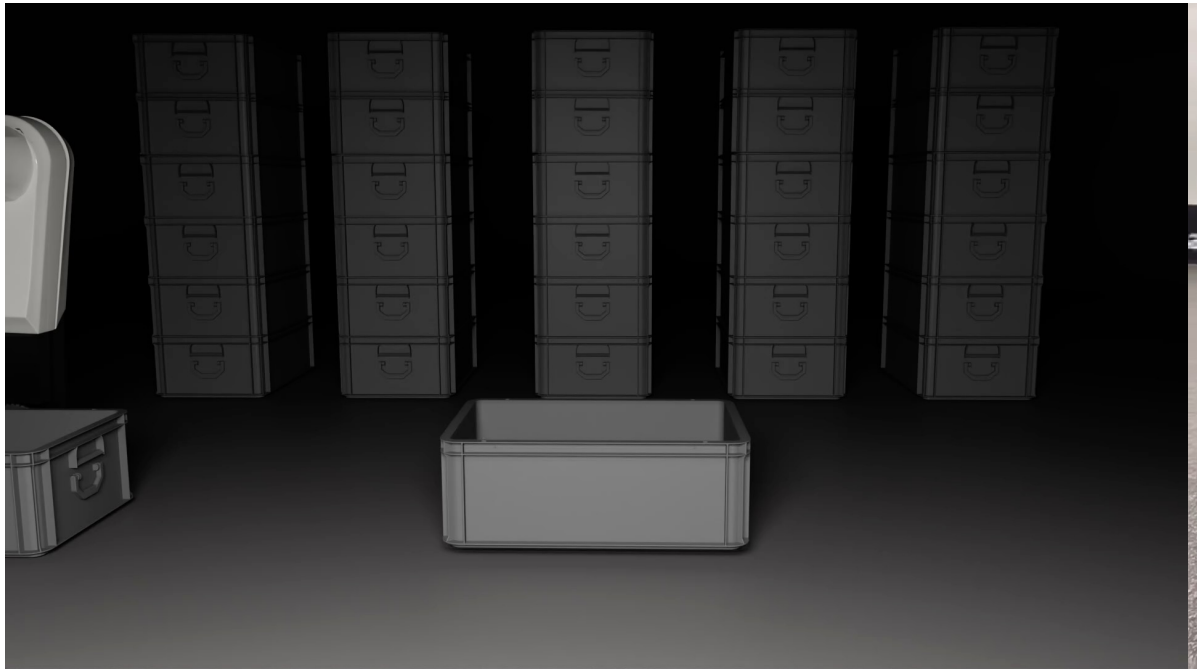
Autonomous Mobile Robots

Example Fraunhofer evoBOT™

Robotic System are becoming more and more versatile



Robot-Robot-Collaboration is coming more into focus

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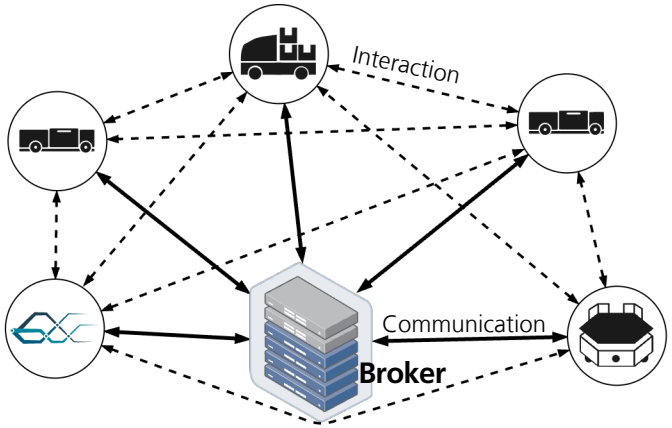
Organization of Communication

Publish-Subscribe [SMD19]

Central organized Communication



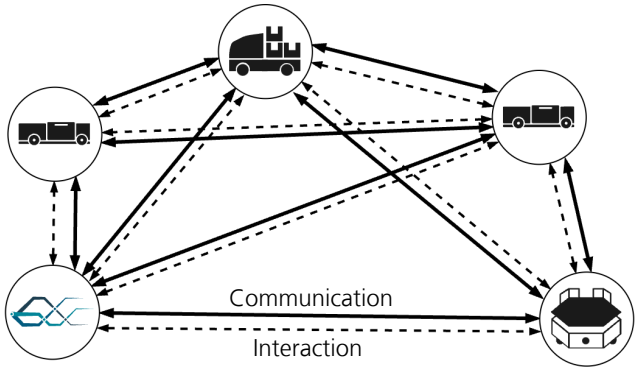
MQTT

ROS
Robot Operating System

orion

...

Decentral organized Communication



OPC UA

DDS

...

Number of Connection Links:

- Participant: $O(1)$
- Broker: $O(N)$

Number of Connection Links:

- Worst-Case: $O(N)$

Star-Topology: Either the *broker* or the *sender* has $O(N)$ connection links

No approach just works on a subset, e.g., $O(n)$ mit $n \ll N$

Icons: Fraunhofer IML
Logos: www.mqtt.org, www.amqp.org, www.ros.org, www.fiware.org, www.opcfoundation.org, www.dds-foundation.org
[SMD19] Shi-Wan Lin; Miller, Bradford; Durand, Jacques; Bleakley, Graham; Chigani, Amine; Martin, Robert; Murphy, Brett; Crawford, Mark: The Industrial Internet of Things Volume

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SOLA: A decentralized communication framework

Overview

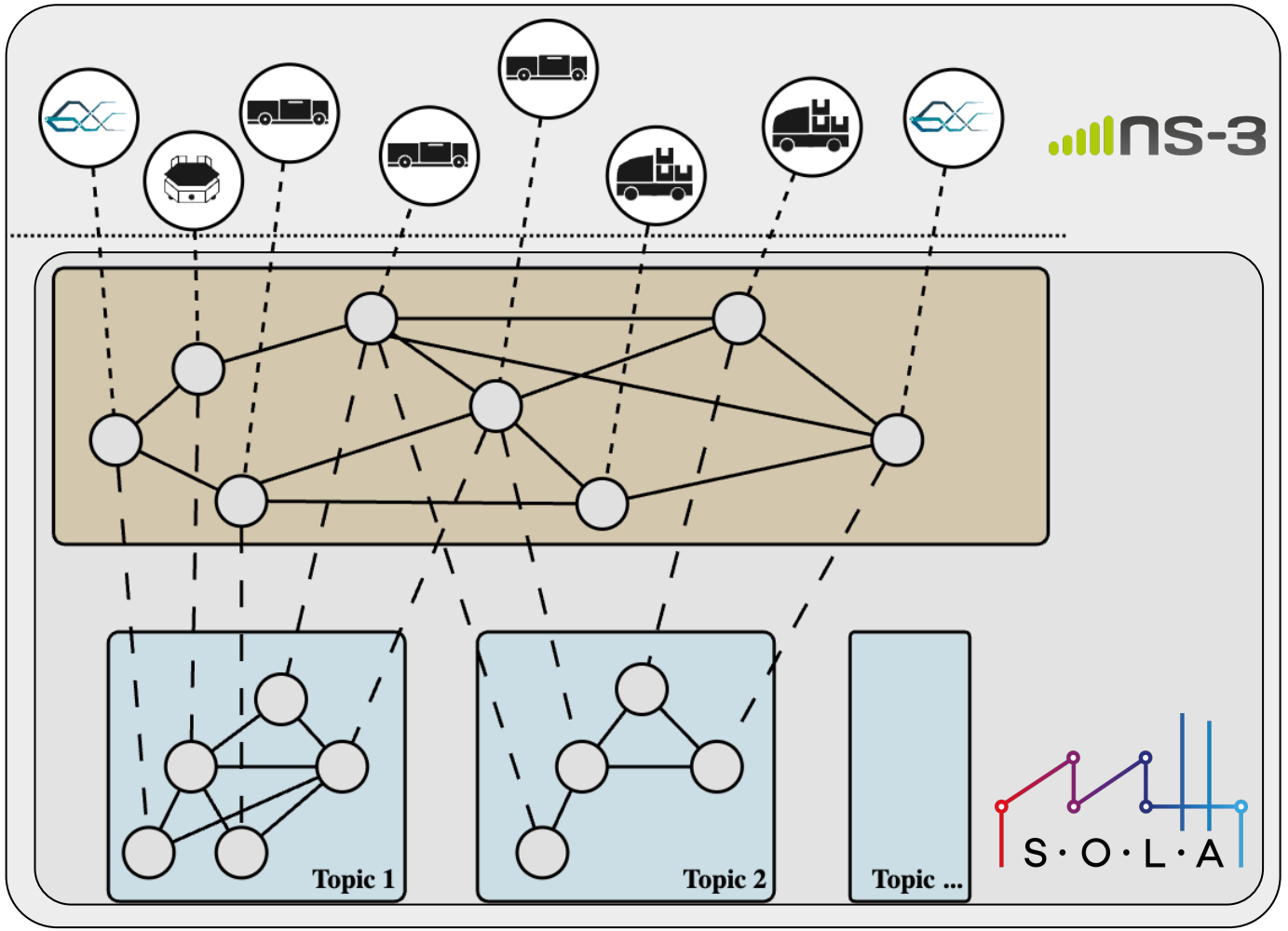
Decentralization on application layer

Management Overlay

- Logical network overlay connecting peers
- Enables lookup for other peers

Event Dissemination

- Topic-based Publish-Subscribe
- $(m:n)$-Broadcast on application layer



Icons: Fraunhofer IML, Figure: own work, ns-3 Logo: www.nsnam.org

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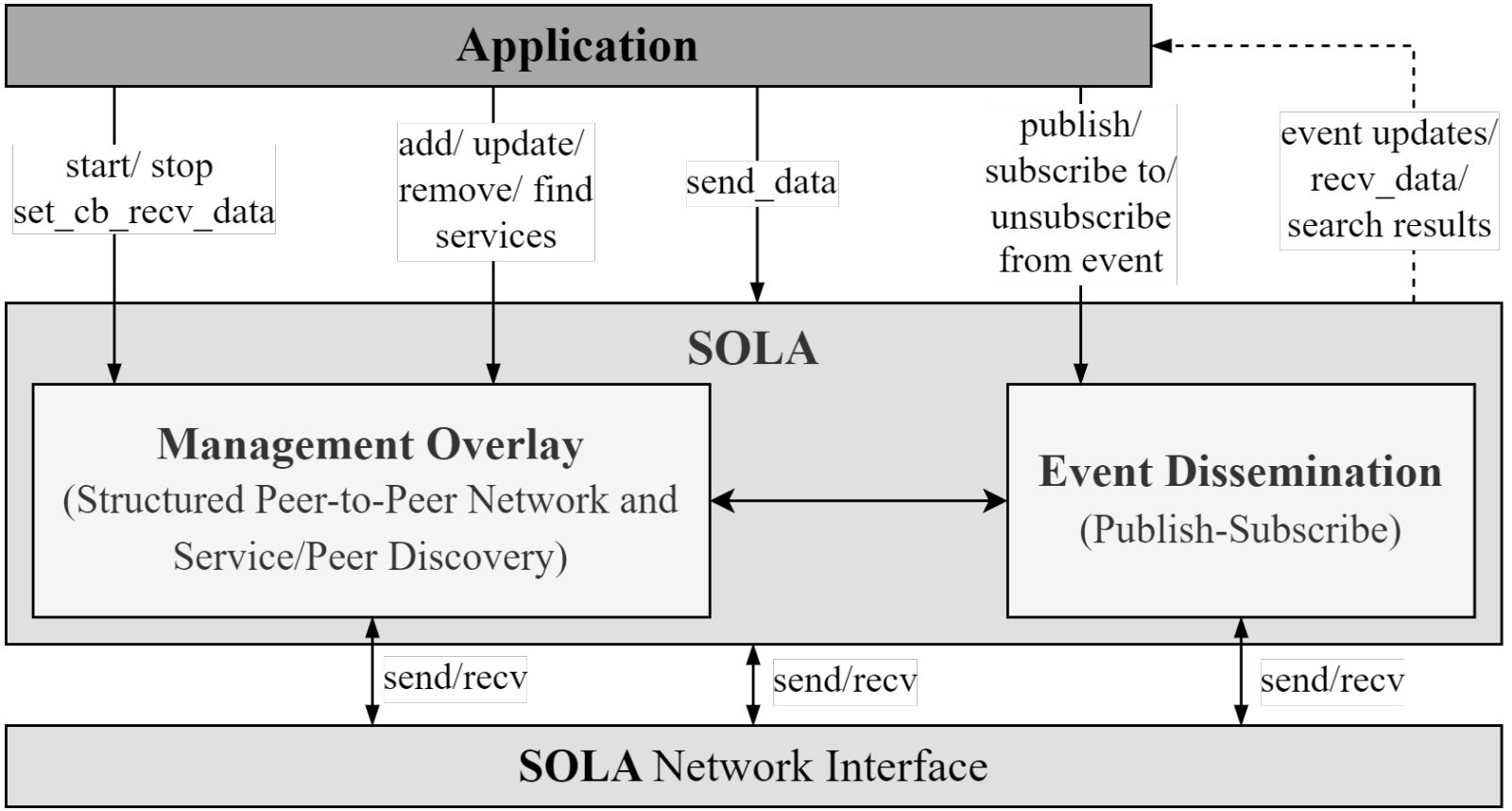
SOLA
A closer look

Simple API

Modular components



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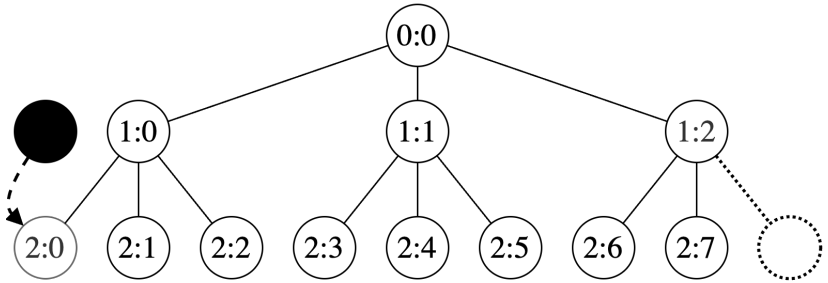
SOLA: Management Overlay

Management Overlay:

- **Minimal height tree overlay network (MINHTON) [LDB23]**
- **Tree overlay network with fixed fanout m**
- **Allows searching for other peers with predicate/ query like $\phi_1 > 42$ [DGB22]**



Join (Hops): $O(m \cdot \log_m N)$

Leave (Hops): $O(m \cdot \log_m N)$

Peer Discovery (Hops):
Insert/Update/Delete: $O(1)$
Search: $O_{BC}(2 \cdot |\mathrm{DSN}|)$

Other structures and protocols could be used as well

[LDB23] Laskowski, Patrick; Detzner, Peter; Bondorf, Steffen: Tree-structured Overlays with Minimal Height: Construction, Maintenance and Operation. In: 17th ACM International Conference on Distributed and Event-based Systems, 2023 (will be presented tomorrow ;-)

[DGB22] Detzner, Peter; Gödeke, Jana; Bondorf, Steffen: Peer Discovery in Tree-Structured P2P Overlay Networks by Means of Connected Dominating Sets. In: 2022 IEEE 47th Conference on Local Computer Networks (LCN), 2022

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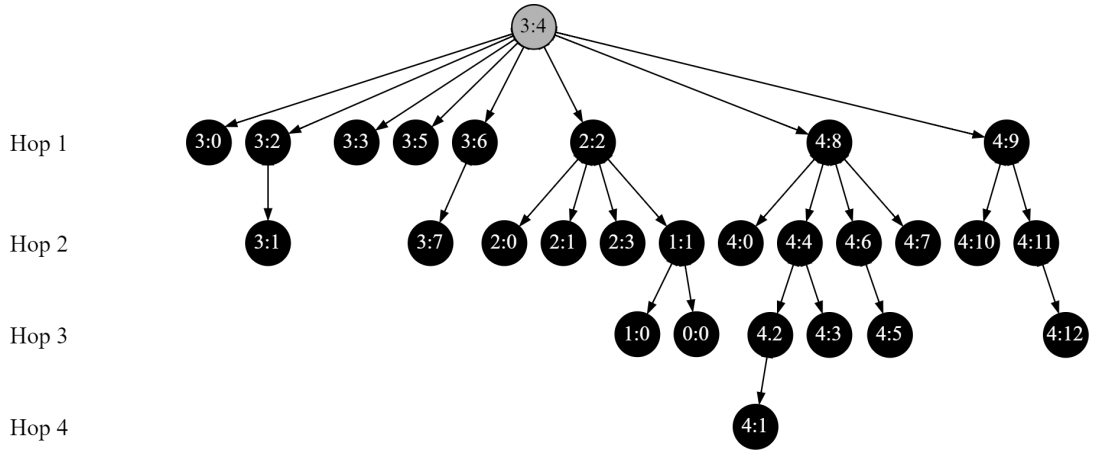
SOLA: Event Dissemination

Costs to subscribe/unsubscribe related to MINHTONs costs

Not sending duplicates (in theory assuming no node failures :-))

Event Dissemination:

- **Deterministic message distribution with Unicasts (Application Layer Multicast)**
- **Uses MINHTON structure for each topic**
- **Creates spanning trees for every initial sender**



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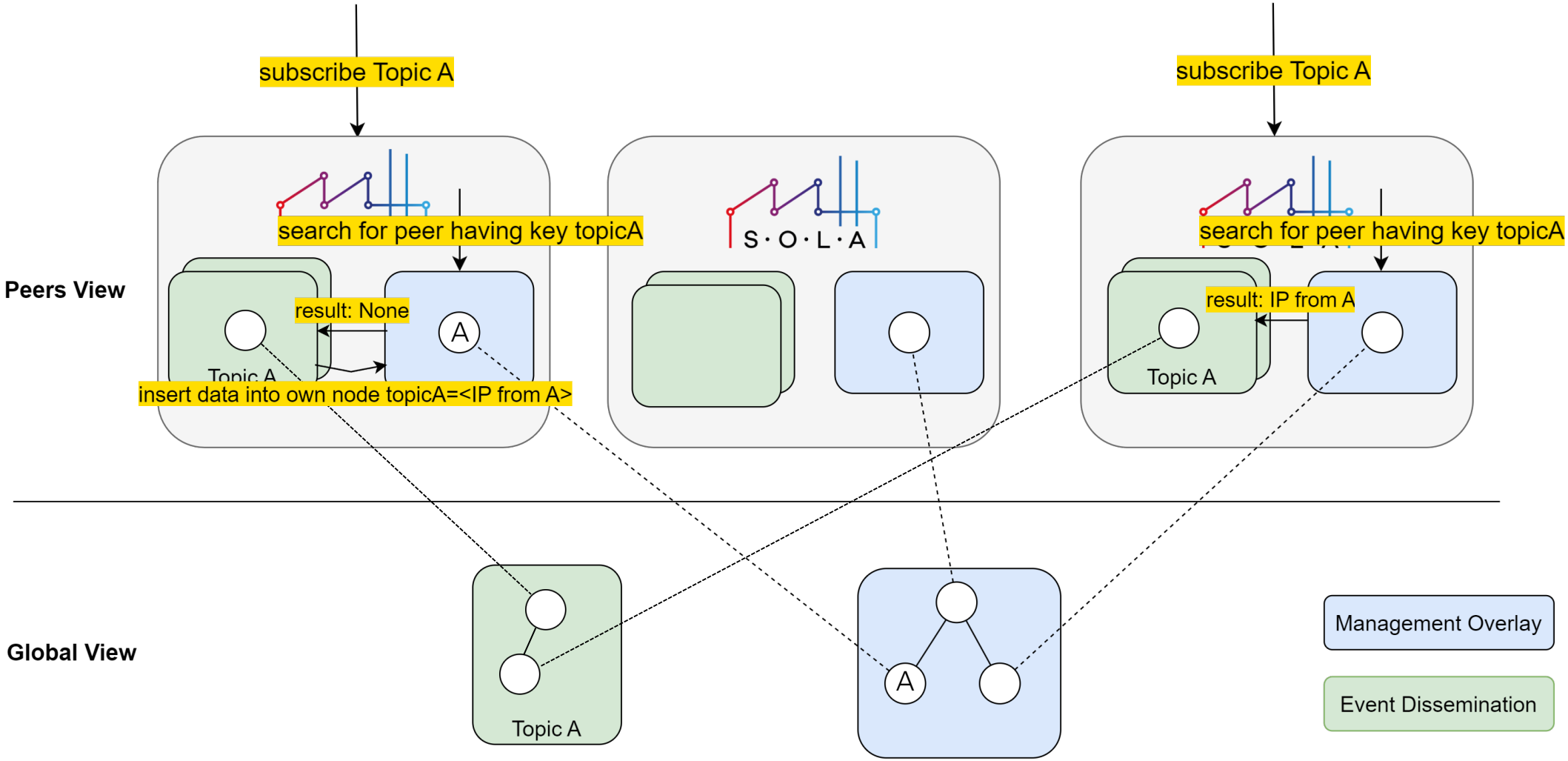
SOLA

Subscribing to a topic



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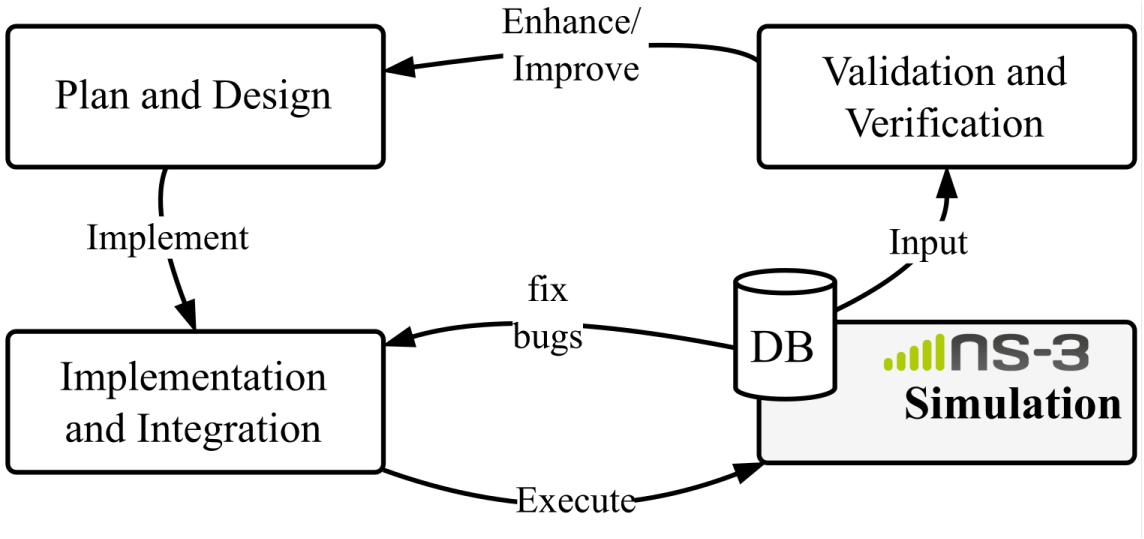
SOLA

Development with ns-3

Key requirements/features:

- **Reproducibility and easy debuggability**
- **Easy configurable application setup**
- **Testing scalability**
- **Validating results**
- **Allow running in simulation or in real-world (using abstractions)**



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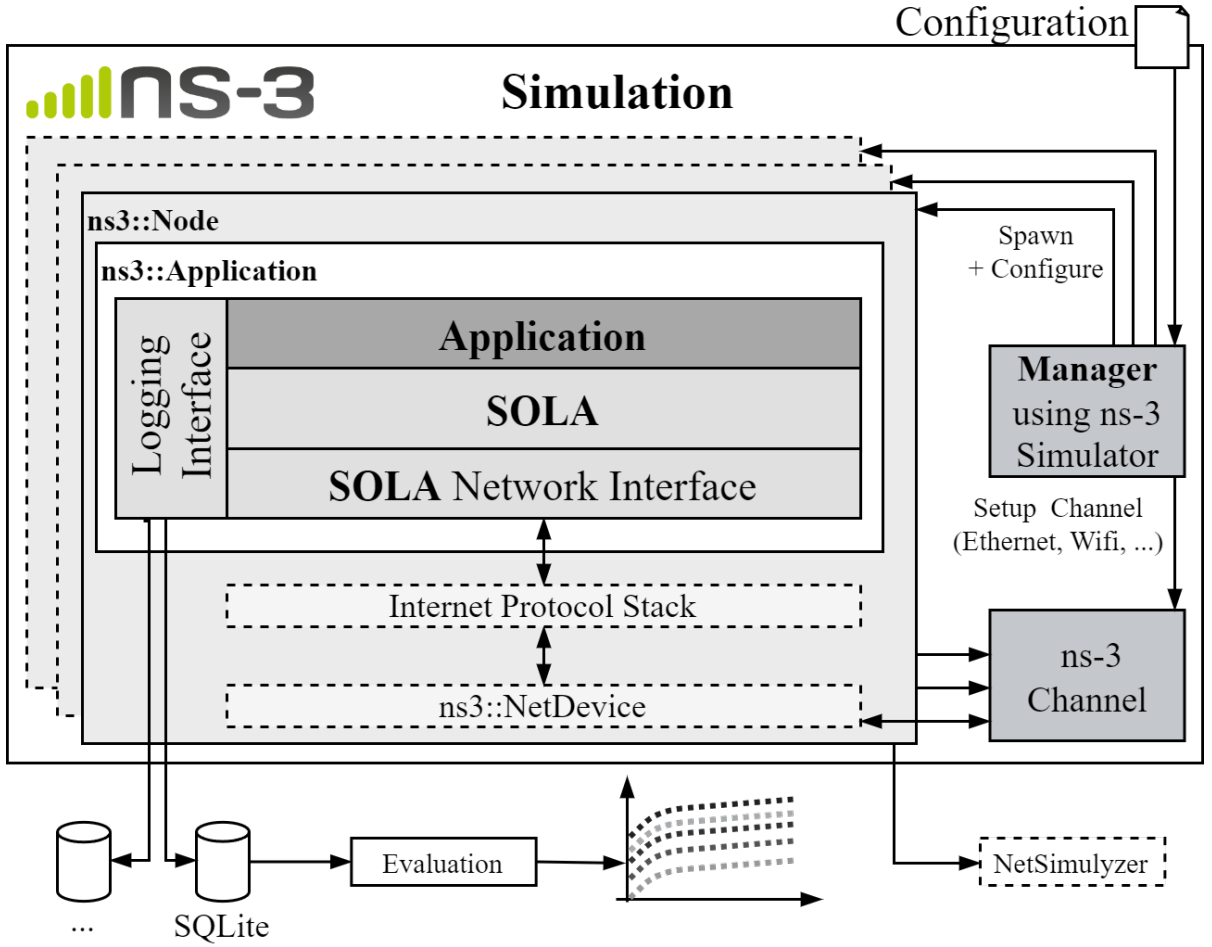
SOLA

Implementation and Integration with ns-3

Key requirements/features:

- **Reproducibility and easy debuggability**
- **Easy configurable application setup**
- **Testing scalability**
- **Validating results**
- **Allow running in simulation or in real-world (using abstractions)**



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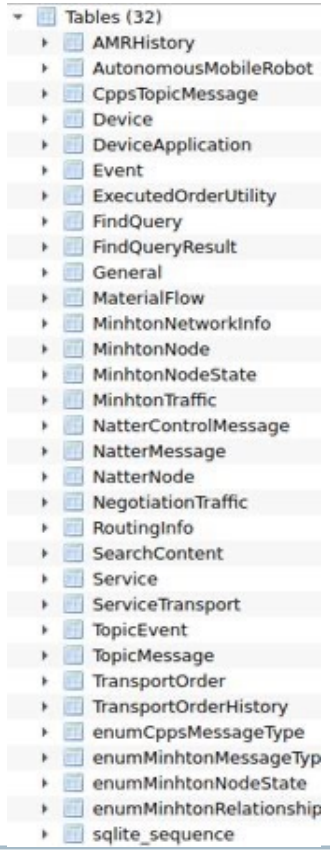
SOLA

Validation and Verification

Logging

- Data is scattered around the network
- Using SQLite in ns-3 simulation
- Using deferred logging
- Abstraction to use other logger mechanisms as well
- Logging for all parts (MO, ED) and on different layers (application, networking)



Scenario Configuration

- Using YAML configuration file
- Passing application and simulation specific configurations
- Automatic parallel execution of different setups

```yaml
- agv1:
    device_type: "agv"
    manufacturer: "FhG_IML"
    model_name: "LoadRunner"
    model_number: "1"
    friendly_name: "LR"
    kinematics:
        min_velo: 0.0
        max_velo: 10.0
        min_acc: -3.0
        max_acc: 3.0
        load_time: 2000
        unload_time: 3000
    ability:
        load_carrier_type: "package"
        max_payload: 30.0
```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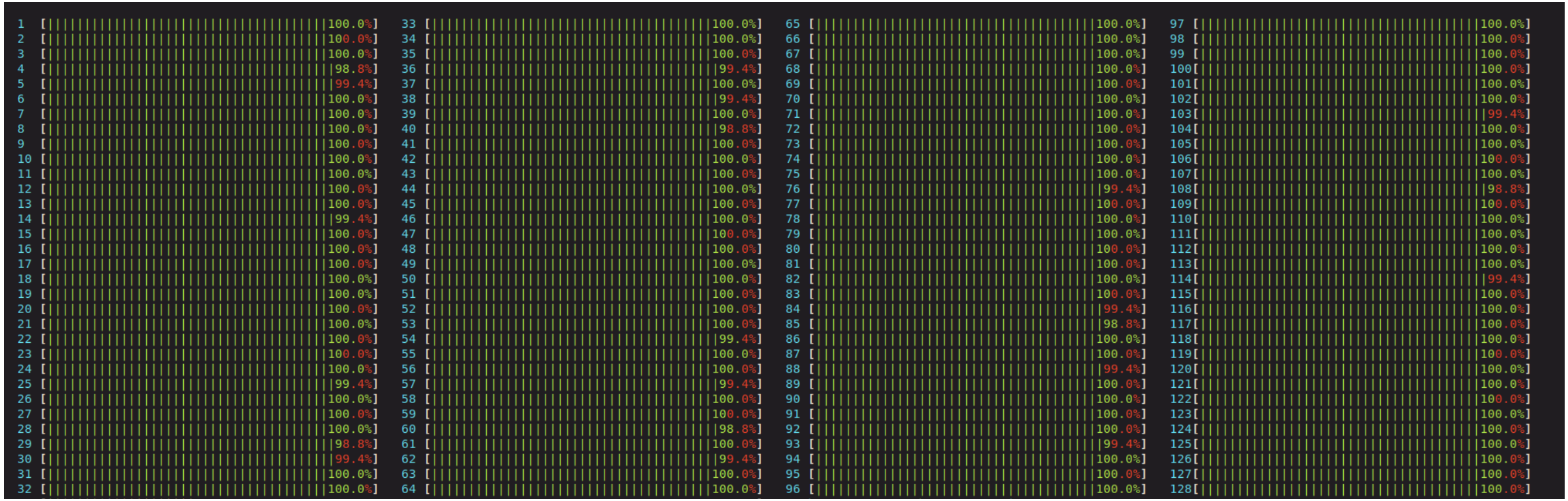
SOLA

Validation and Verification

Logging | **Scenario Configuration**



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SOLA

ns-3 network structure

Layer

Transport

- UDP
- No node failure and package loss

Internet

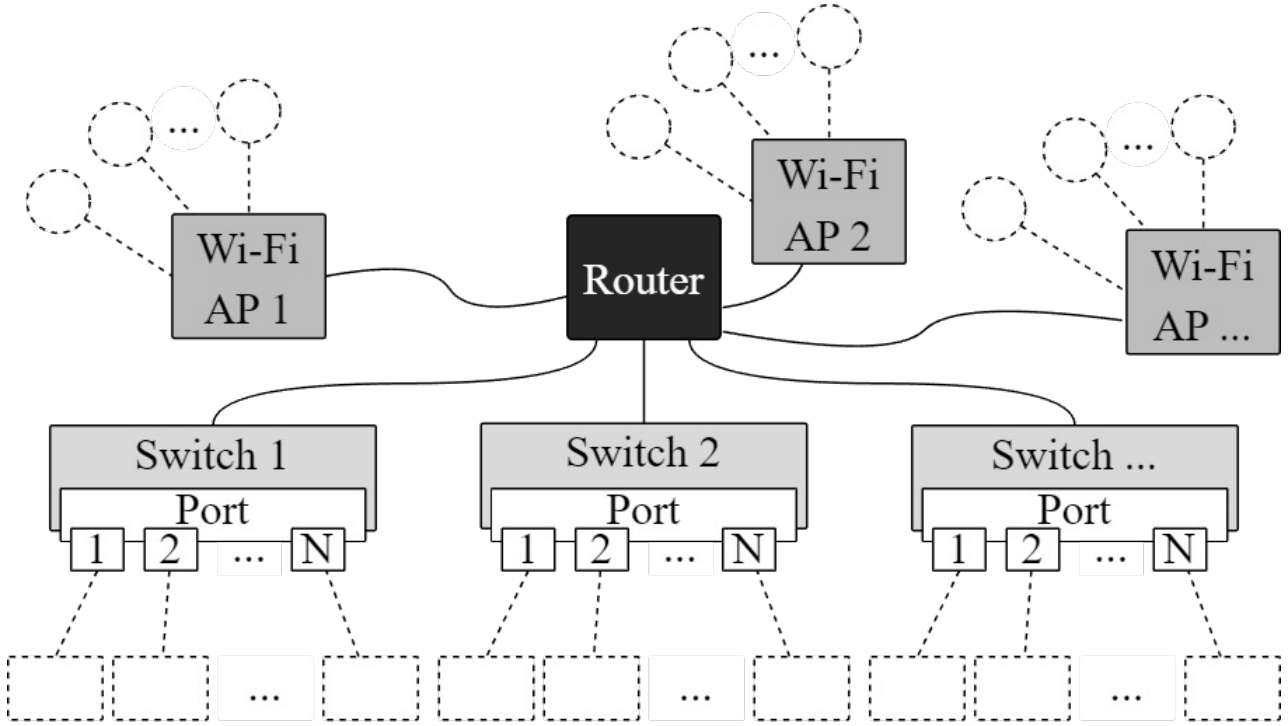
- Separate IP subnets
- Static IP routing

Link

- ns-3 CSMA model
- ns-3 wireless model
- Using pre-filled ARP tables [MAD19]

Communication topology:

- Application layer: decentralized
- Link layer: star-topology (centralized)



[MAD19] Madden: Challenges Using the Linux Network Stack for Real-Time Communication. AIAA Scitech 2019 Forum, 2019

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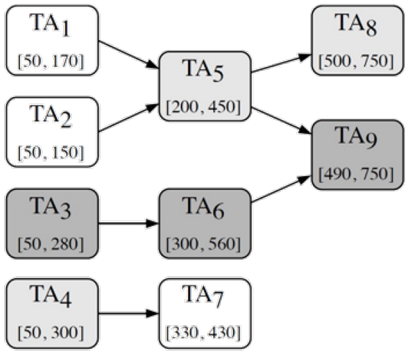
Use Case: Self-Organized Material Flow

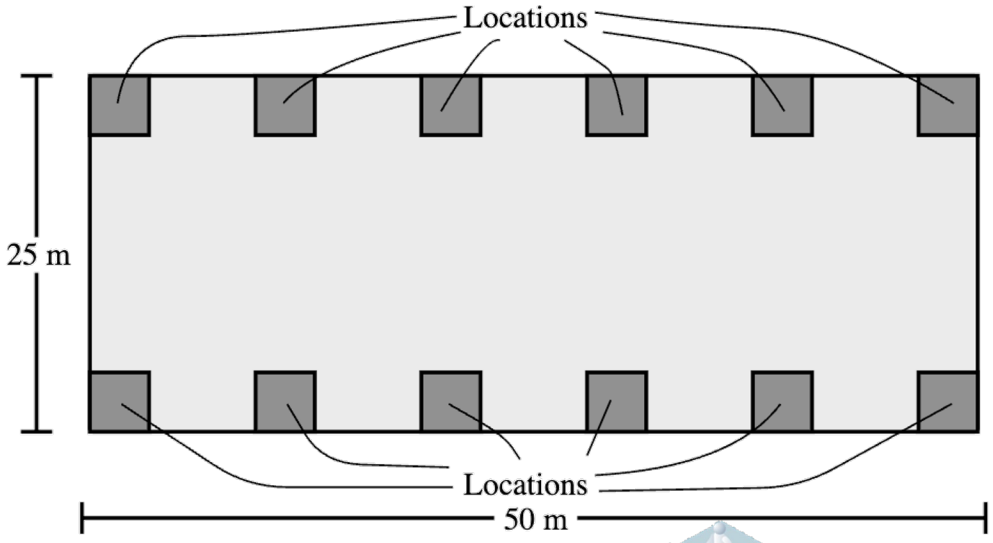
Initial Setup

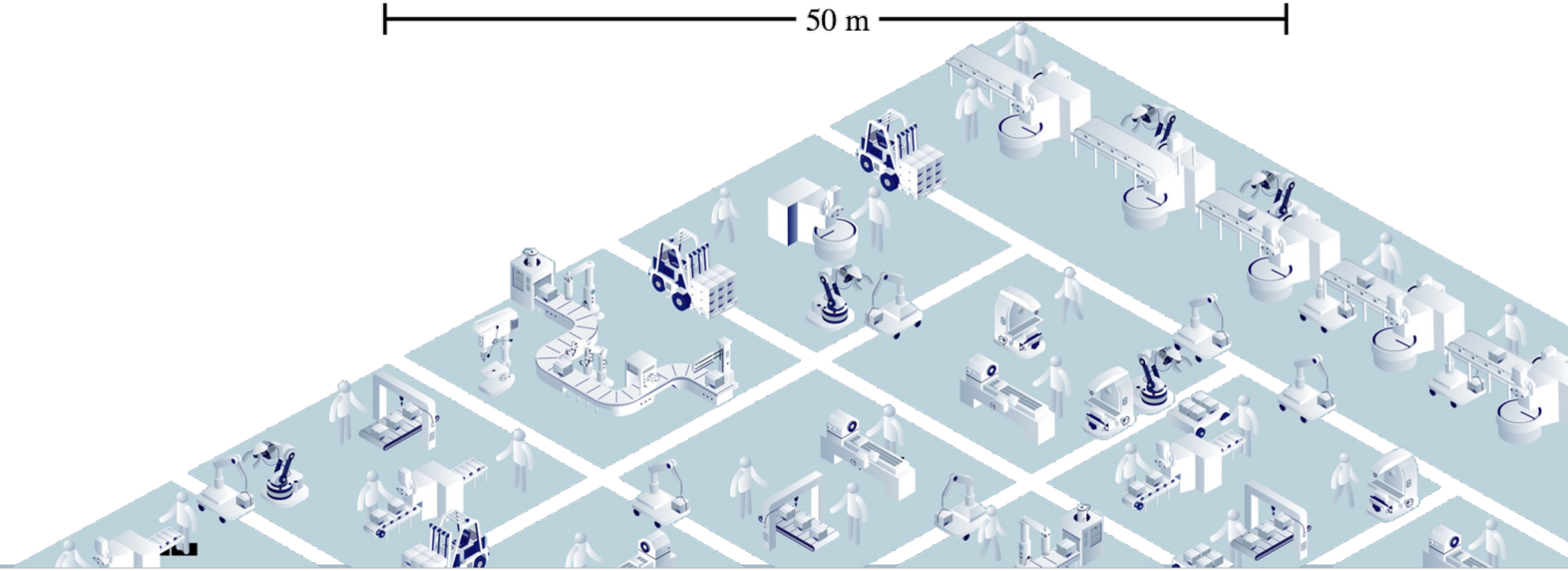
Precedence Graph with 9 Transport Orders

Temporal Constraints (Deadlines)

Heterogenous AMRs







Icons and Figures: Fraunhofer IML

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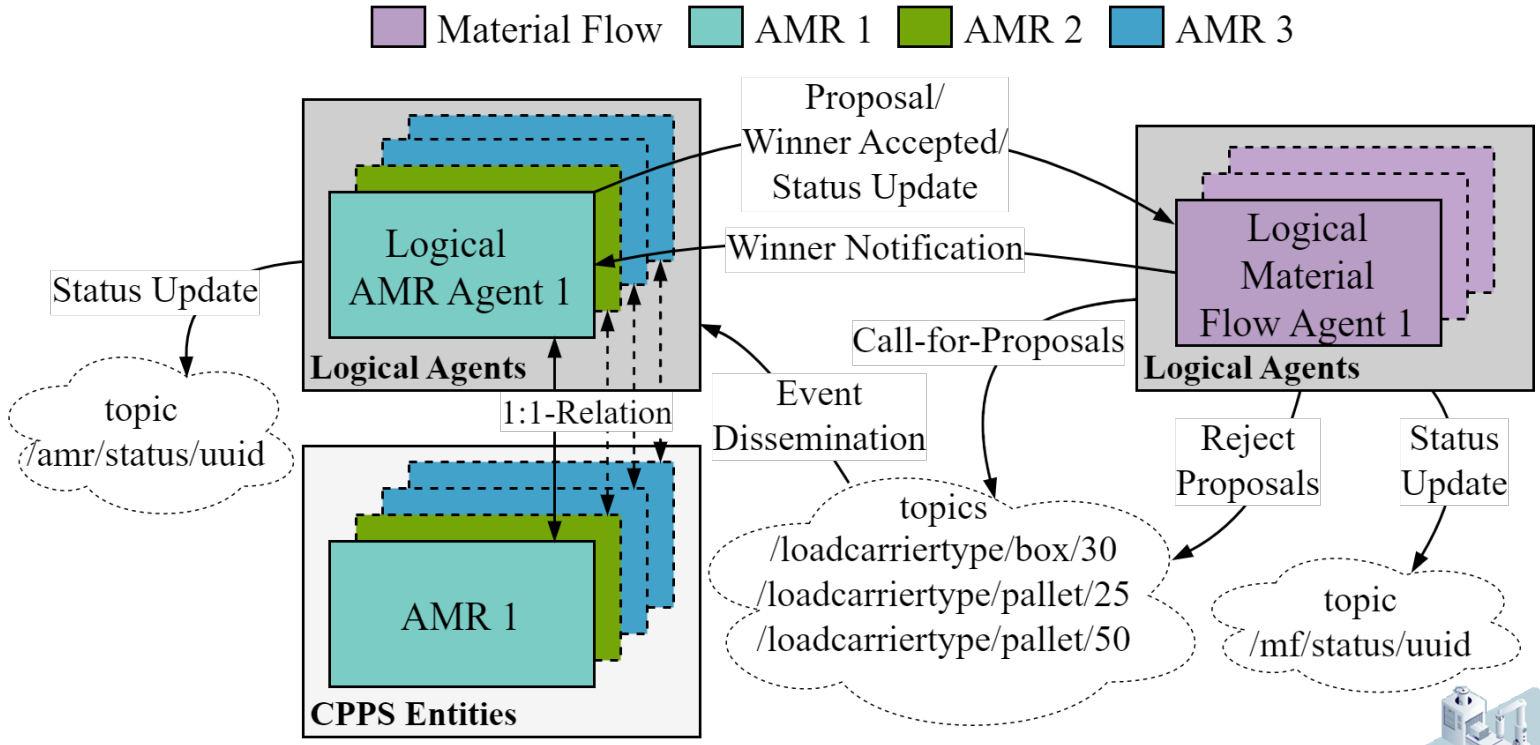
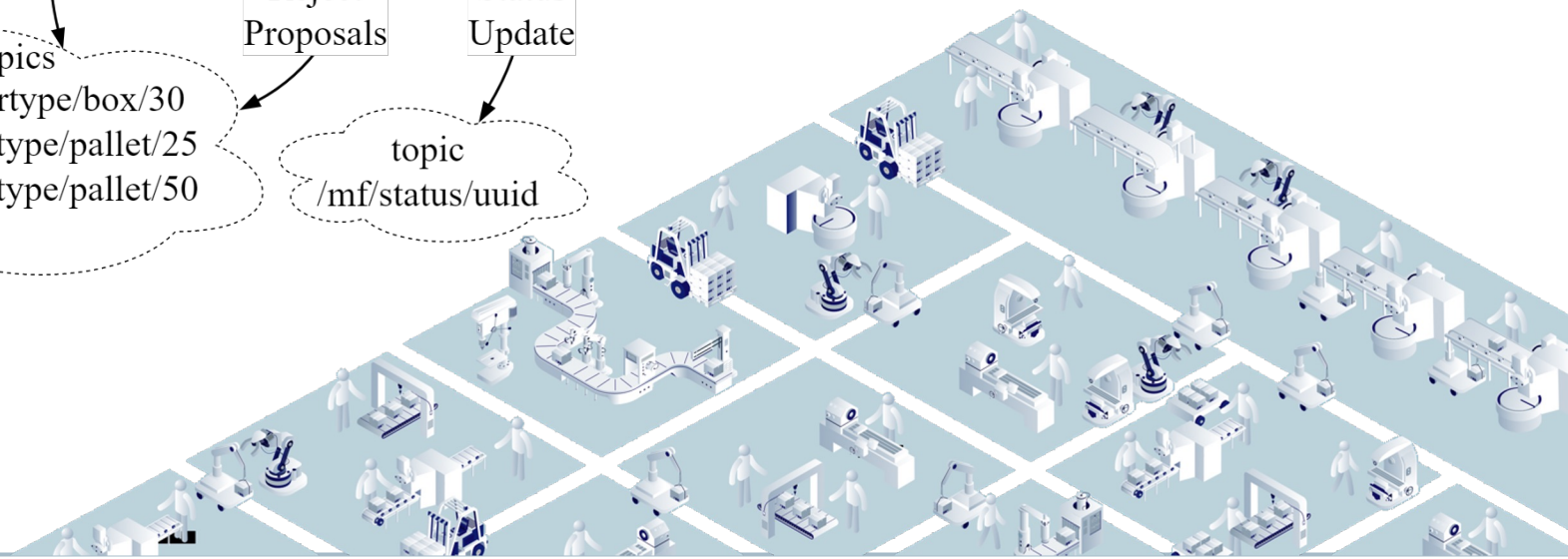
Use Case: Self-Organized Material Flow

System Design





Icons and Figures: Fraunhofer IML

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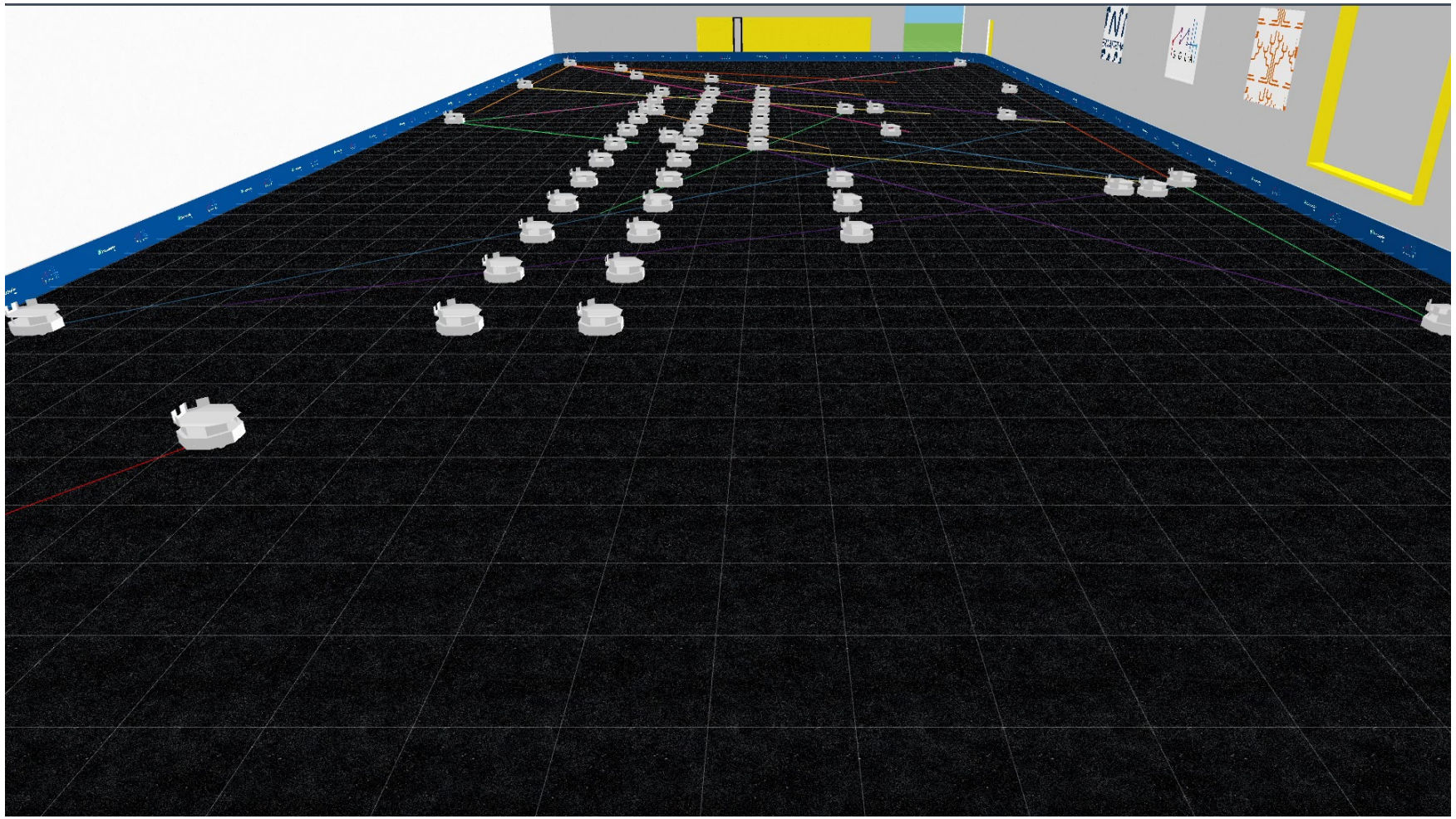
Use Case: Self-Organized Material Flow

Visualization with NetSimulyzer [BGR21]



[BGR21]: Black, Evan and Gamboa, Samantha and Rouil, Richard: NetSimulyzer: a 3D network simulation analyzer for ns-3. In: WNS3 '21: Proceedings of the 2021 Workshop on ns-3, 2021

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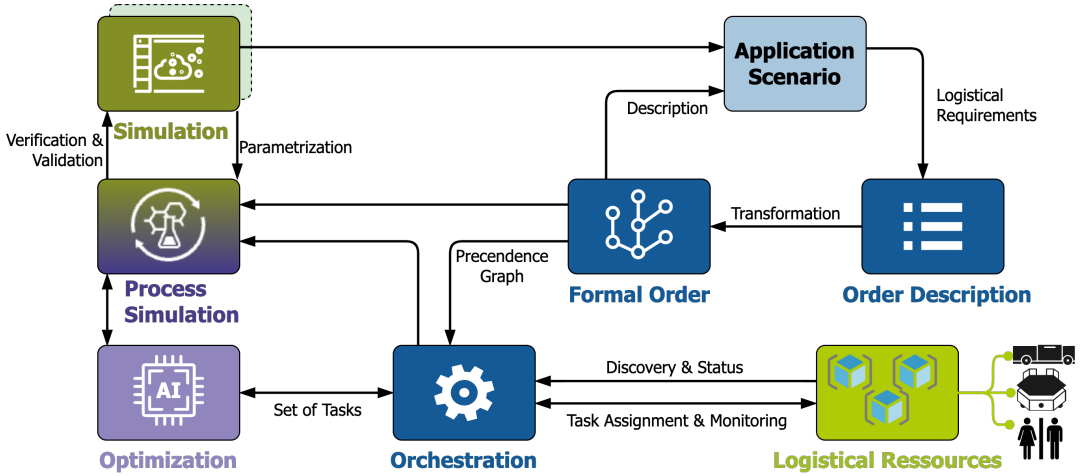
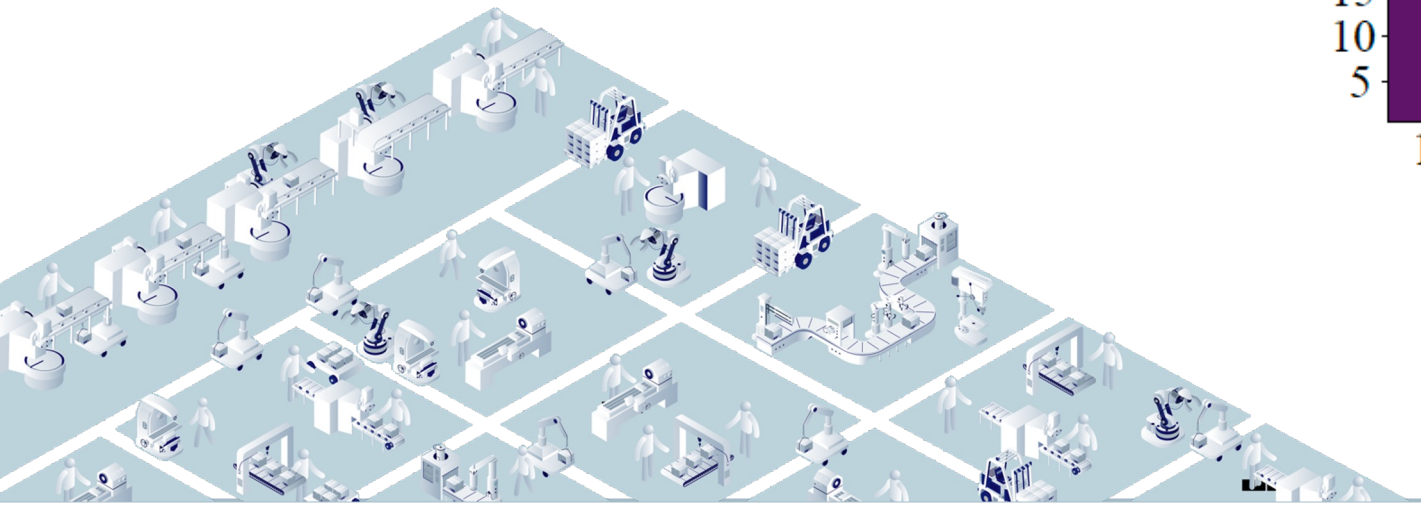
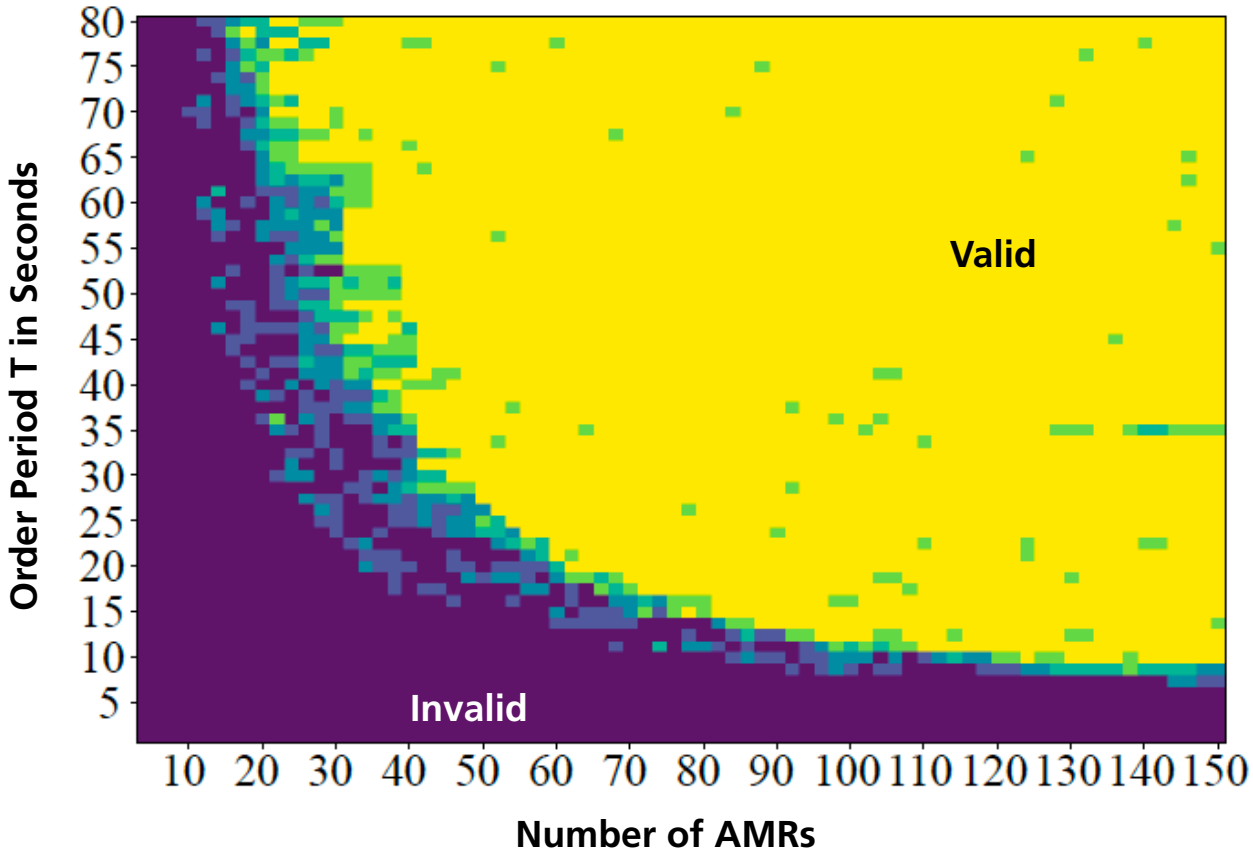
Use Case: Self-Organized Material Flow

Solution Space







Icons and Figures: Fraunhofer IML

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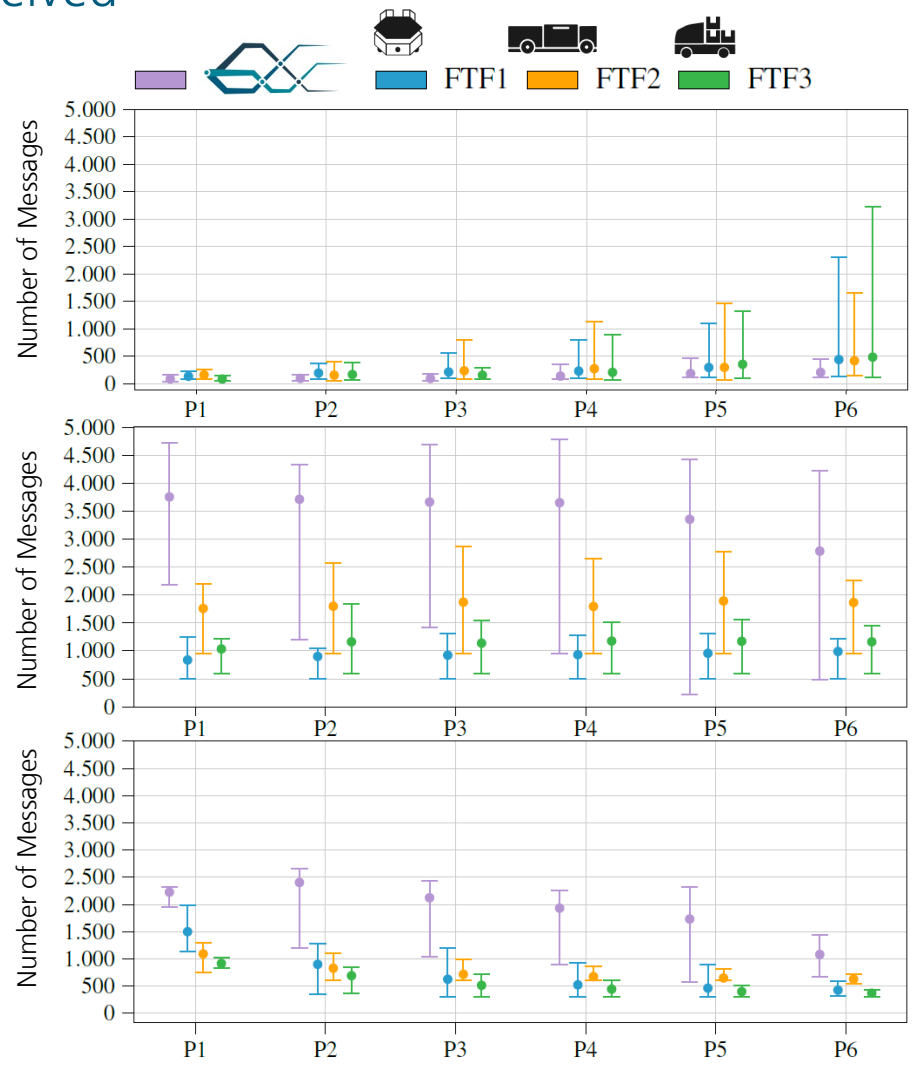
Use Case: Self-Organized Material Flow

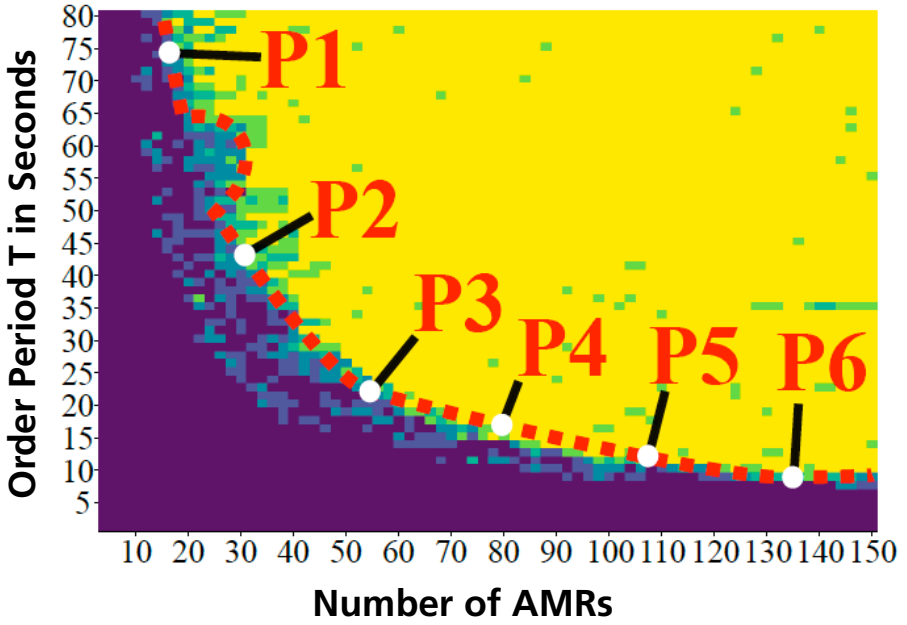
Messages sent and received

Management Overlay

$(m:n)$ Event Dissemination

(1:1)-Communication





Parameter	P1	P2	P3	P4	P5	P6
Order Period T in Seconds	78,75	63,75	37,5	26,25	17,5	8,75
Number AMRs	16	30	54	78	108	138
Number Material Flows	8	10	17	24	34	66
Overall Number of Participants	24	40	71	102	142	204

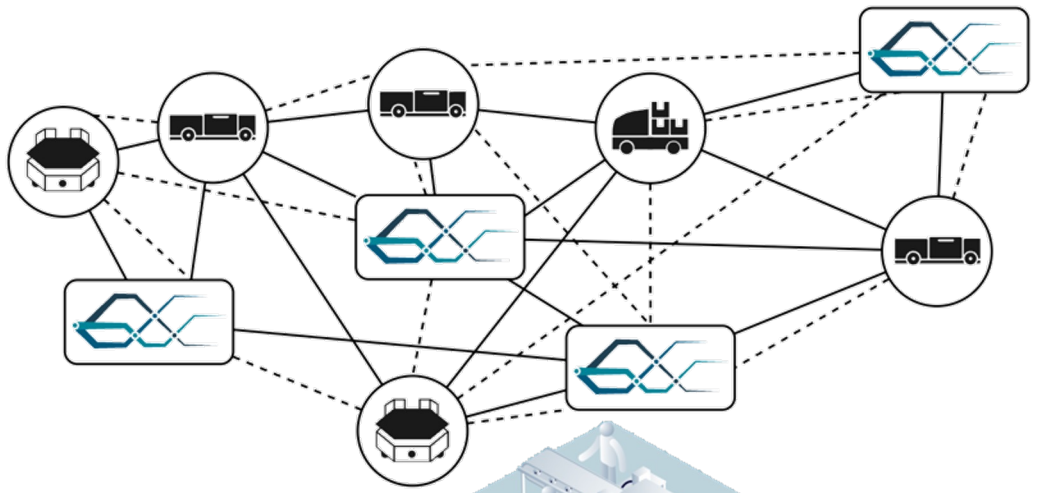
Icons: Franhofer IML, Figures: own work

Conclusion

Decentral organized communication SOLA

Fully developed and integrated with ns-3

Proof-Of-Concept with Self-Organized Material Flow



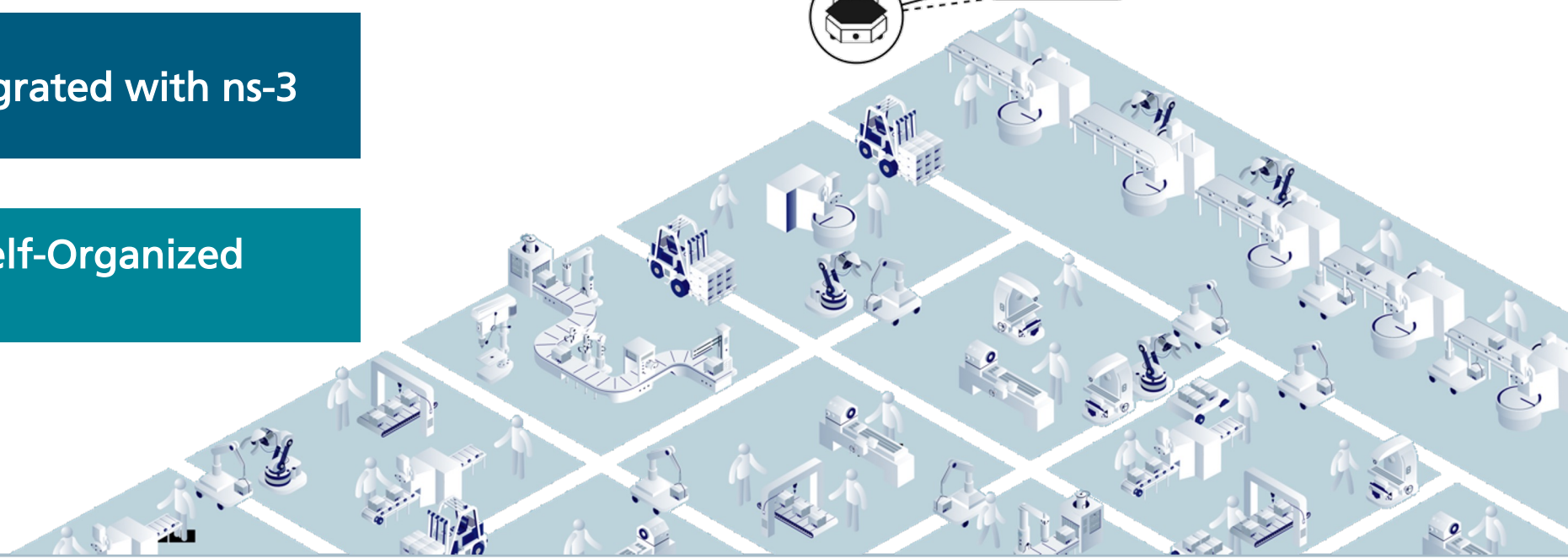


Image: Fraunhofer IML

Fraunhofer IML

Future Work

Deployment in real-world

SOLA
(Cost reduction: Peer Discovery, exploiting local view, …)

Connecting to other simulations, e.g., ROS2, NVIDIA, …

Optimization

Network: QUIC, 5G, Mobile Ad-Hoc Networks, Vehicle Ad-Hoc Networks, …

Image: Adobe, ns-3 Logo: www.nsnam.org

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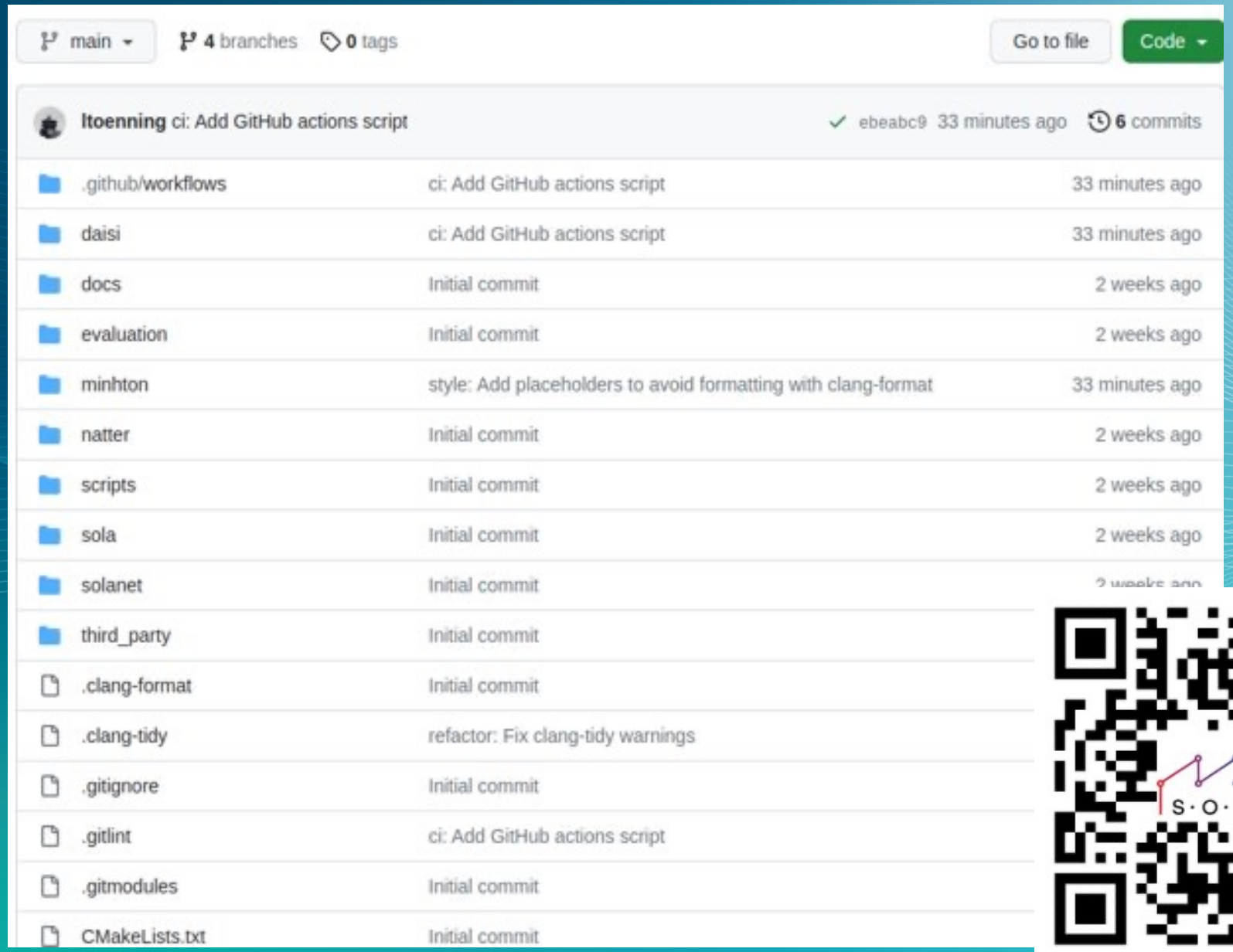

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Thank you for your attention!

Questions?

https://github.com/iml130/sola